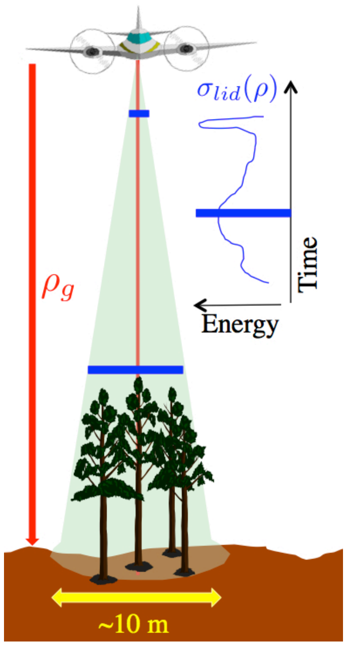
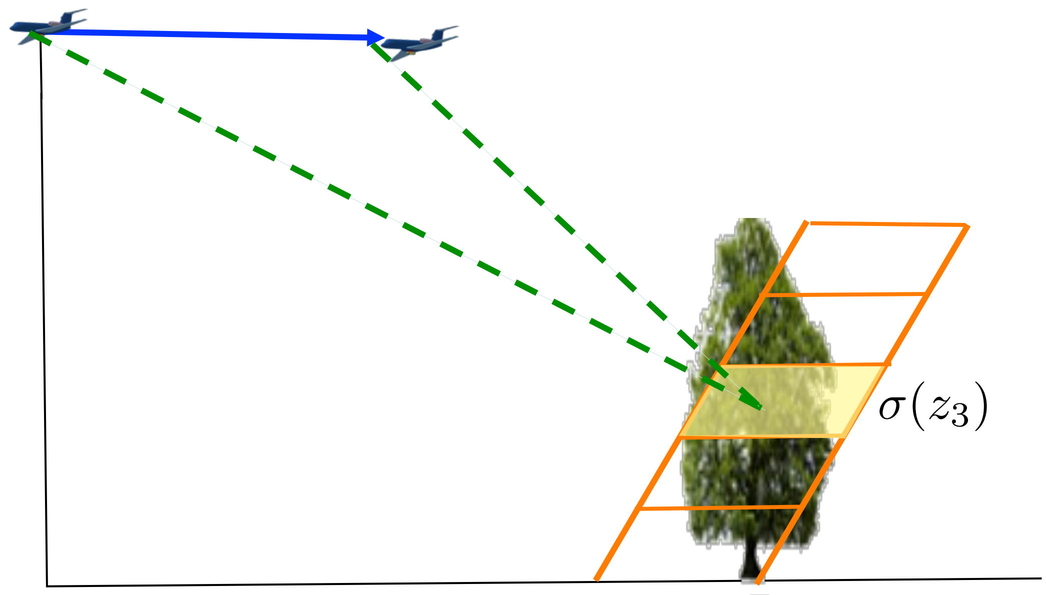
What is InSAR/PolInSAR, and Why Might It Be Useful for Ecosystem Studies?





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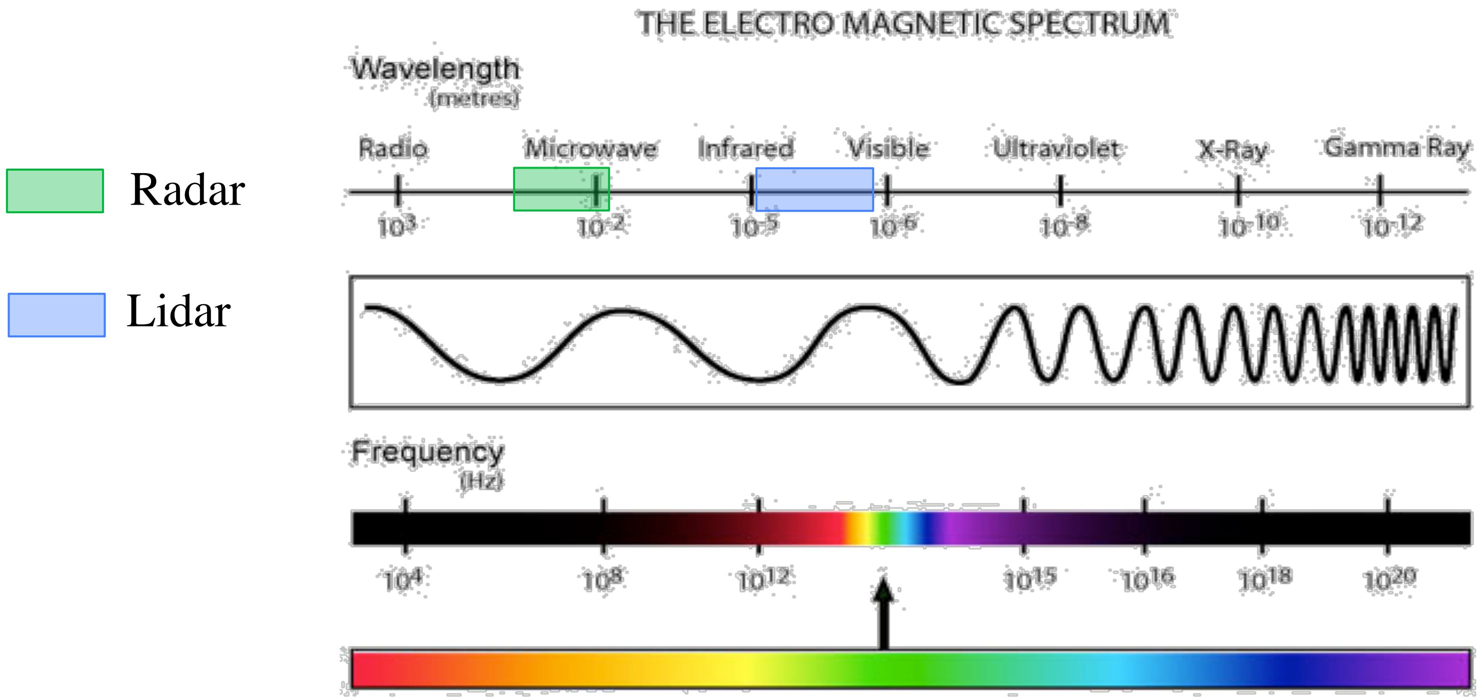
NASA Carbon Cycle and Ecosystems
Joint Science Workshop
Alexandria, Virginia

Understanding InSAR/PolinSAR

- Lidar has become the de facto standard for the remote sensing of vertical structure in vegetation due to:
  - the fine vertical resolution – meter class or better
  - the fine horizontal resolution – 1 m – 100 m depending on platform and sensor
- In this talk our goal is to show how radar interferometry (InSAR) and polarimetric radar interferometry (PolinSAR) sense vertical structure and how they might be useful for ecosystem studies.
- To get an intuitive understanding of how these techniques work we present a comparison with lidar measurement techniques and illustrate how they work in an ecosystem context.

Lidar and Radar Wavelengths

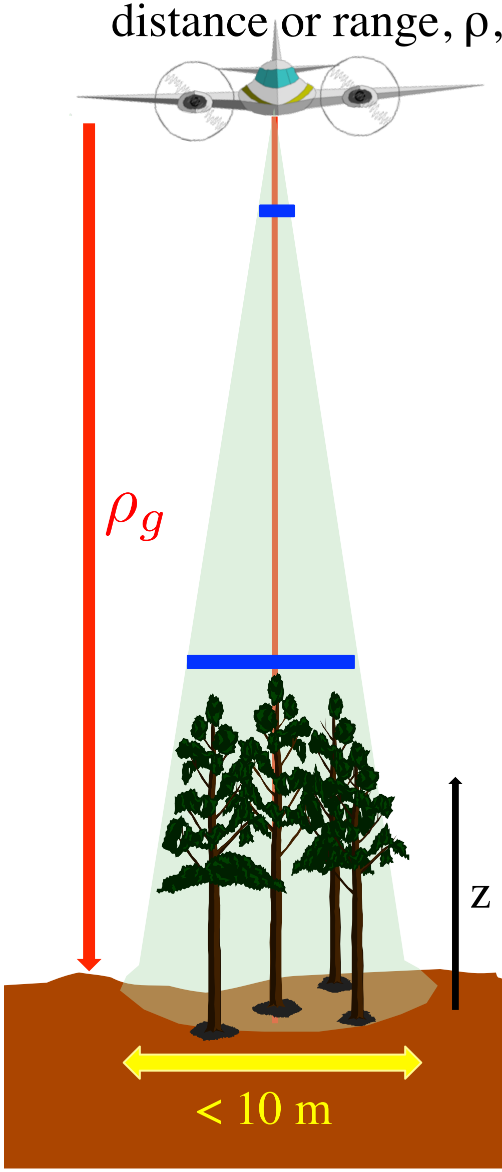
- Both radar and lidar are remote sensing devices that emit electromagnetic waves (light) and record the reflected signals.

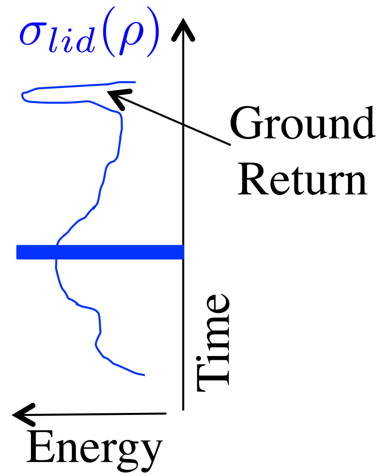


- Radar waves are about 100000 times longer than lidar waves!
- Because of the difference in wavelength
  - Radar and lidar waves fundamentally interact very differently with vegetation
  - The sensor configuration and parameters are quite different

What does a lidar measure?

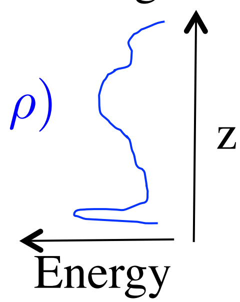
- Lidar emits a narrow pulse of infrared light which reflects off the canopy and ground and records the strength of the returned signal, $\sigma_{lid}(\rho)$, as a function of time or equivalently, distance or range, ρ, from the sensor.





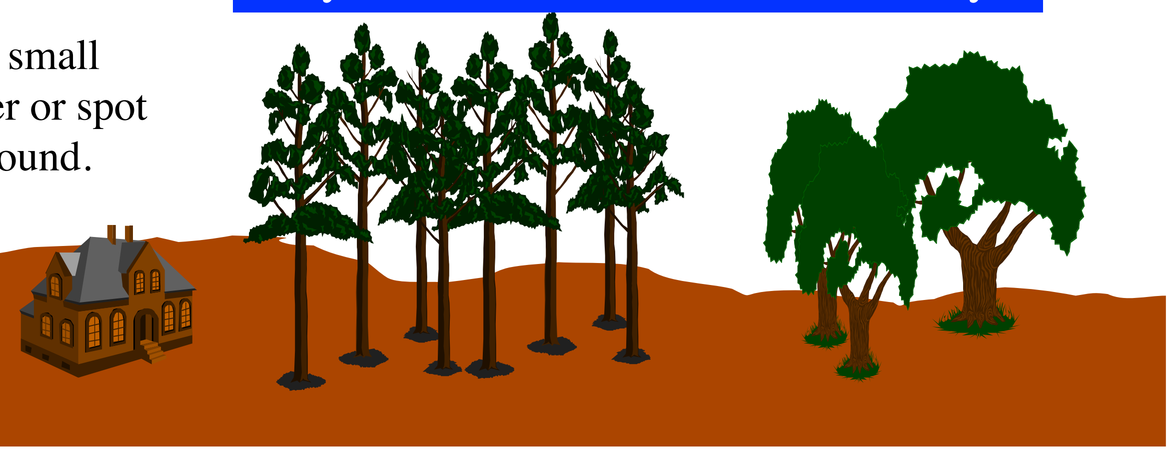
- The range to the ground, ρ_g, is identified as a peak in the returned signal.
  - This is not always obvious.
- The vertical structure as a function of height, z, in the vegetation is then given

$$\sigma_{lid}(z) = \sigma_{lid}(\rho_g - \rho)$$



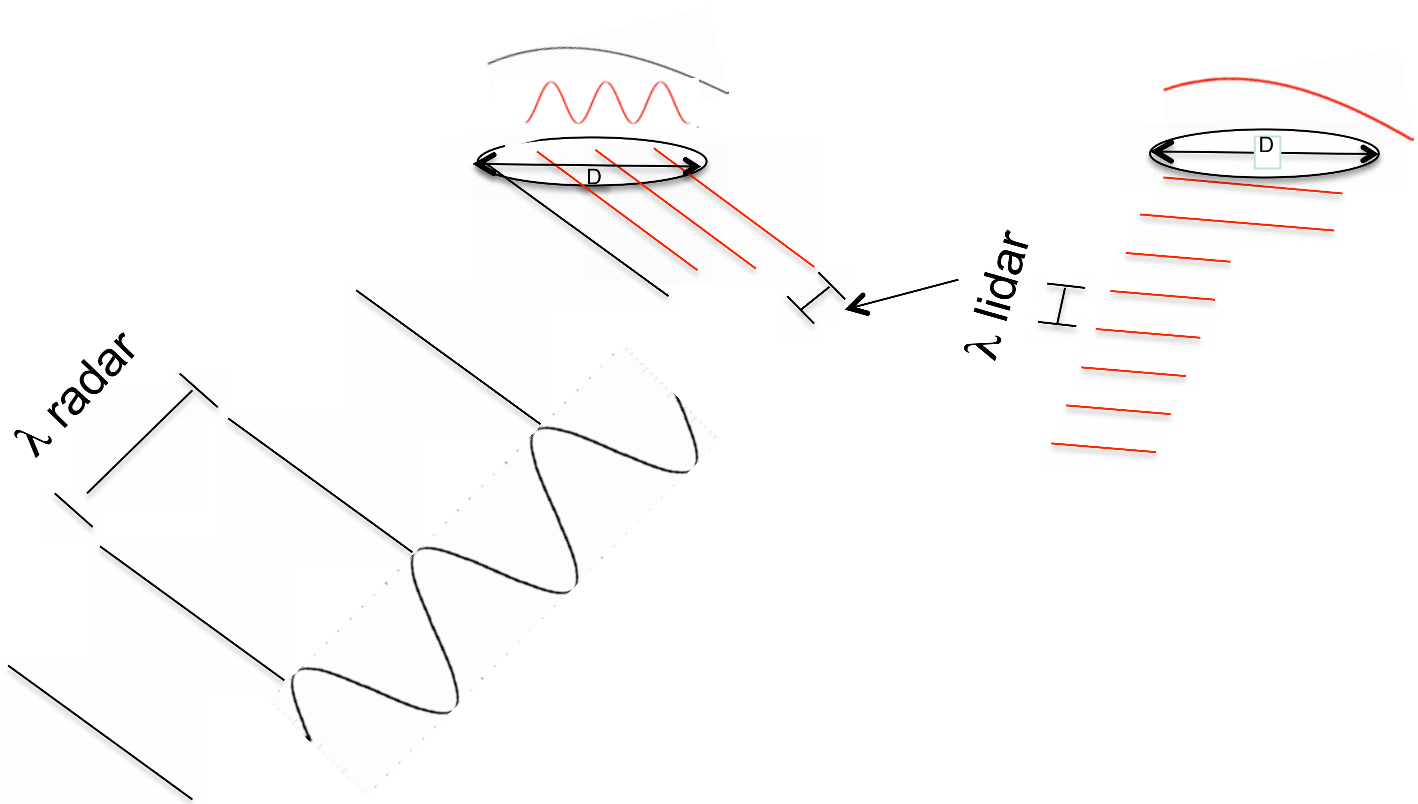
Lidars have a small beam diameter or spot size on the ground.

Why doesn't radar work the same way?



Wavelength and Angle of Emission?

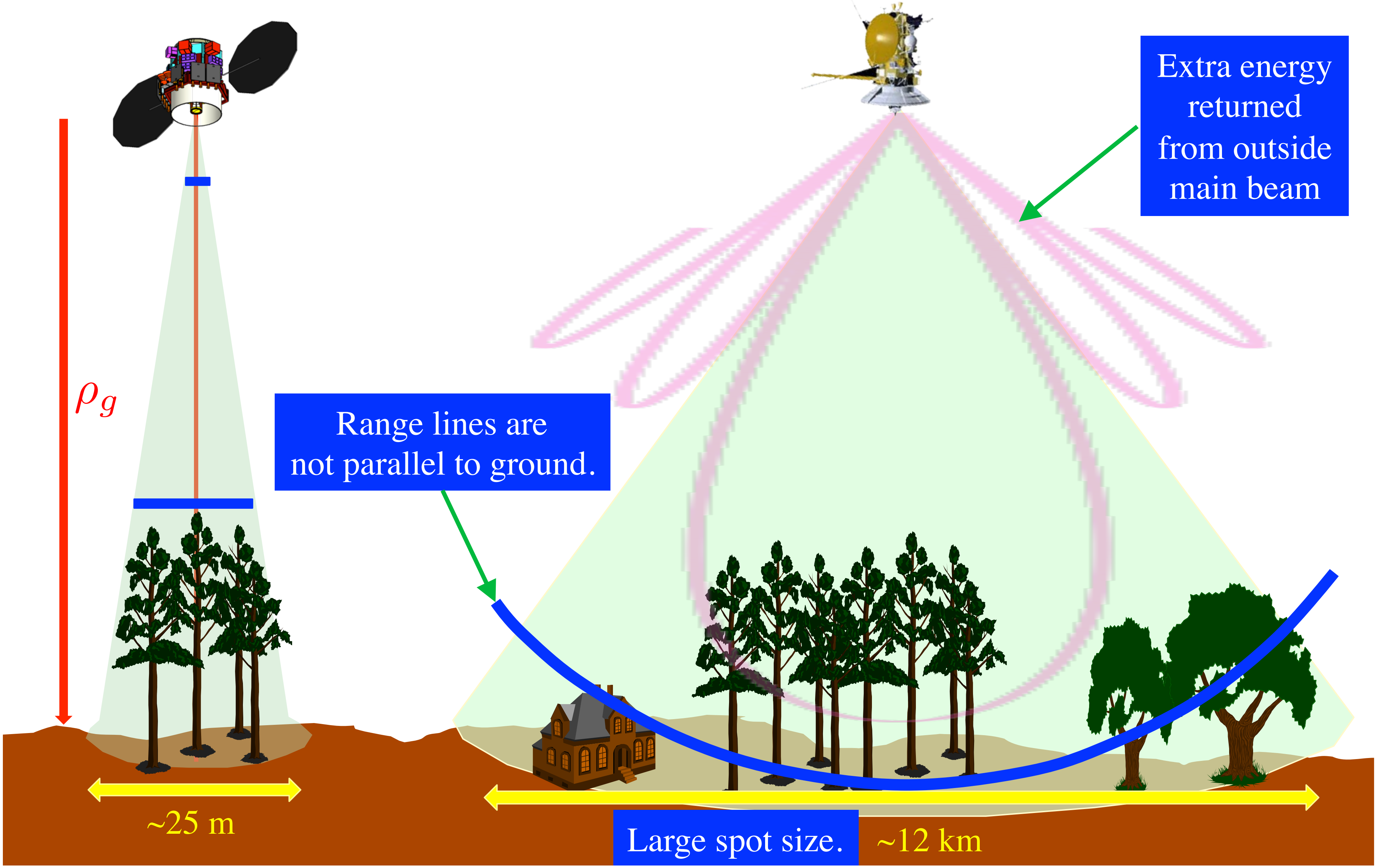
- To understand why radars are not nadir looking like lidars we need to first understand how these instruments focus their energy on the ground.
- Angle of emission depends on wavelength, λ, and diameter of lens or antenna, D.



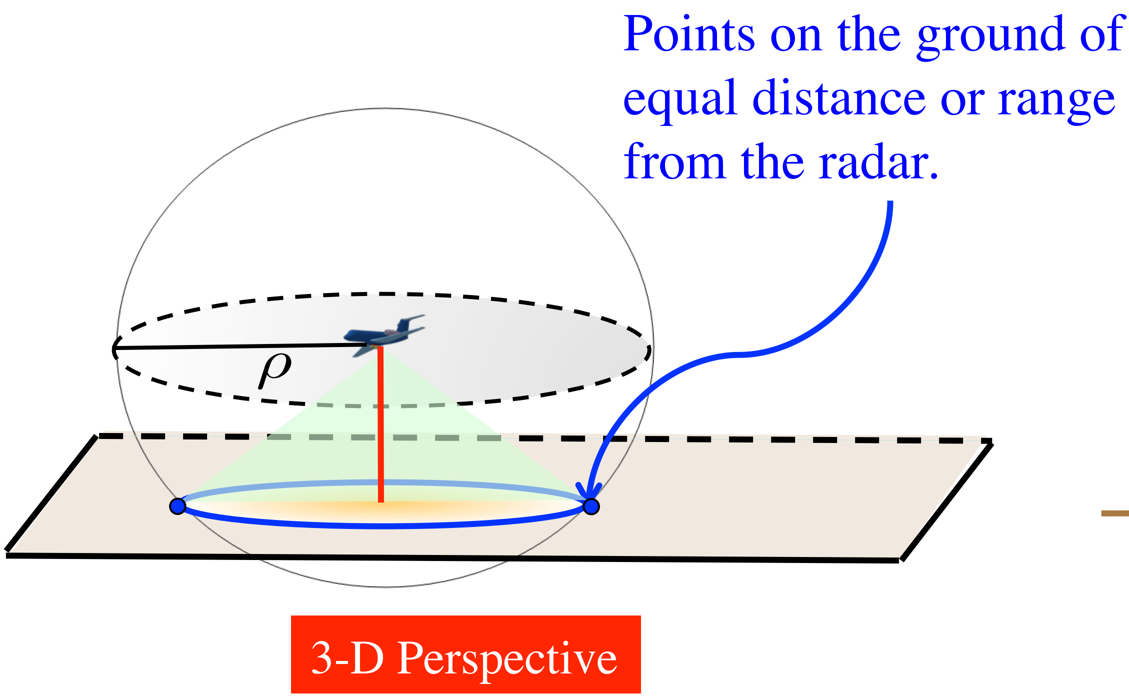
- Radar angle (spot)>> Lidar angle (spot)…by factor of 20 cm/1 micron~10^5 for same size lens or antenna.

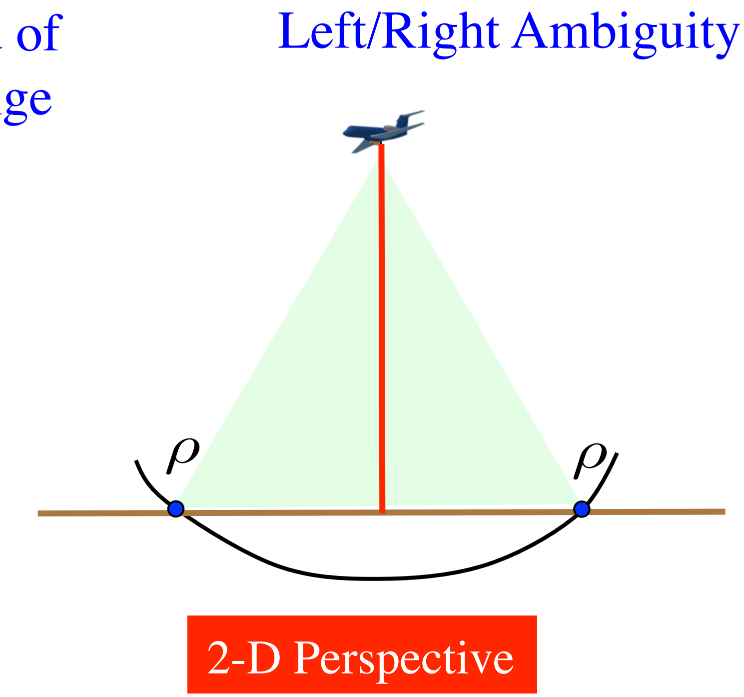
Why Don't SARs Look Down Like a Lidar?

- Nadir looking radar spot size induces several problems not encountered by lidar.



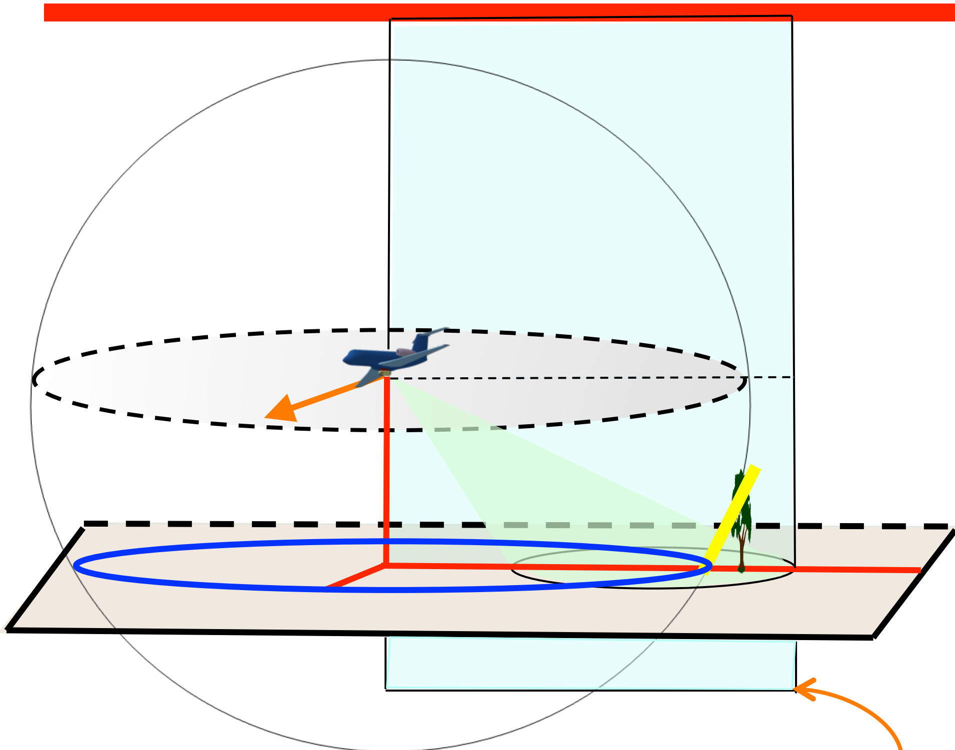
Nadir Looking Radars Lack 2-D Resolution



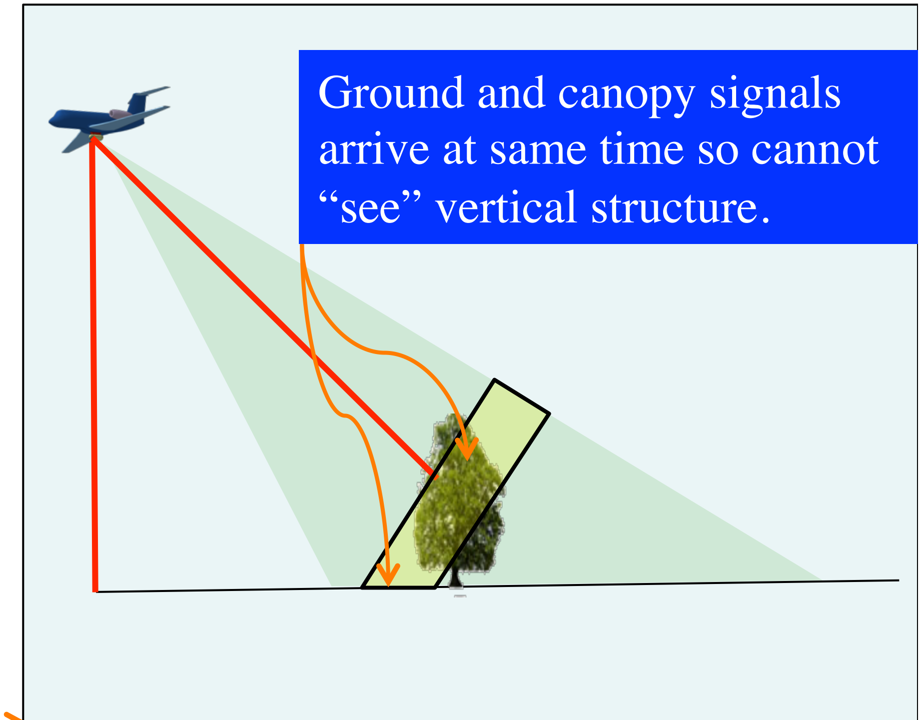


- Returns from points along a circle all arrive to the radar at the same.
- Cannot separate returns from left or right or forward or rear of aircraft
  - Can't achieve fine spatial resolution required for ecosystem studies
- So how can radar solve this problem?
  - This is where the magic of synthetic aperture radar or SAR plays a role.

SAR - Looking to Side!



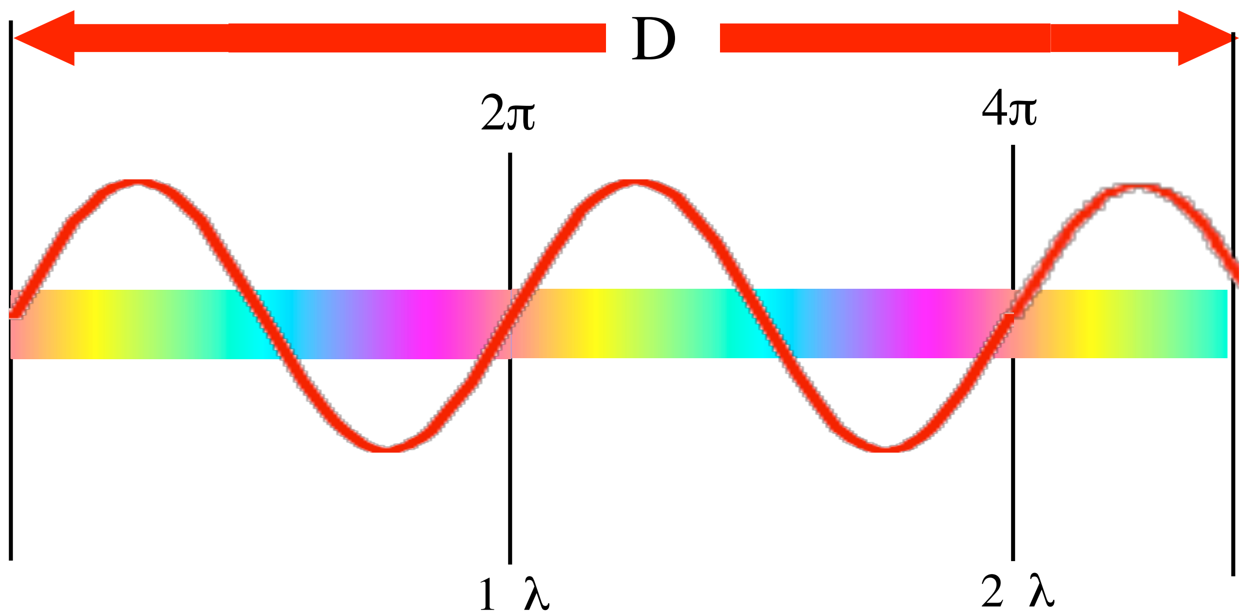
SAR separates and locates points in the along-track direction



- By looking to the side and using the magic of SAR points can be separated in the along-track direction.
- Radar imagery now has fine spatial resolution in both range and azimuth.
- Now the bad news…
  - Range coordinate still does not separate points vertically in vegetation.
- Need a new idea to try and separate information vertically.

Phase to Distance Relationship

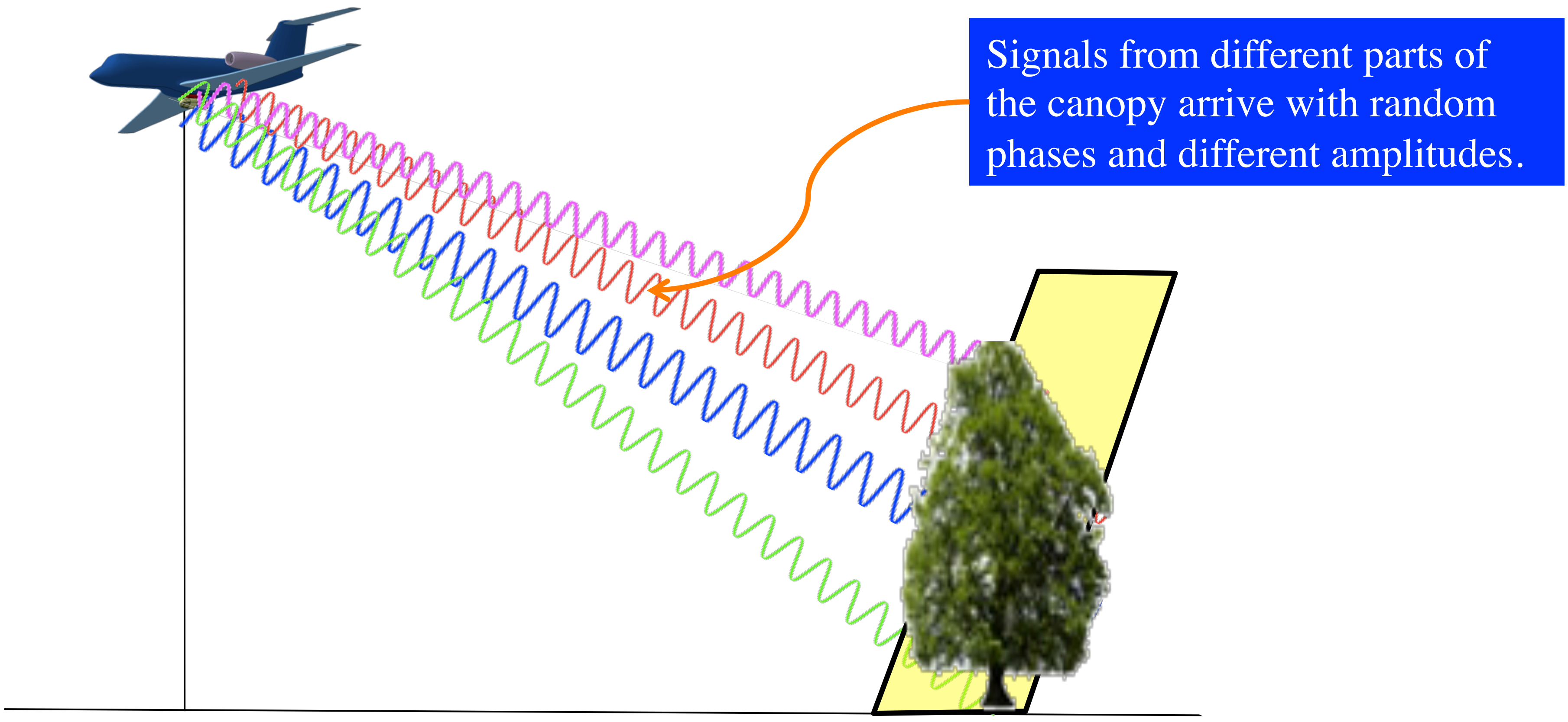
- Distance can be measured in wavelengths – there are many more lidar wavelengths than radar wavelengths for the same distance.
- Phase is simply the distance in wavelength multiplied by 2π.



$$\text{Phase} = \underbrace{2\pi}_{\text{Radians per Wavelength}} \underbrace{\frac{L}{\lambda}}_{\text{Number of Wavelengths}}$$

Vertical Structure Obscured by Random Phase

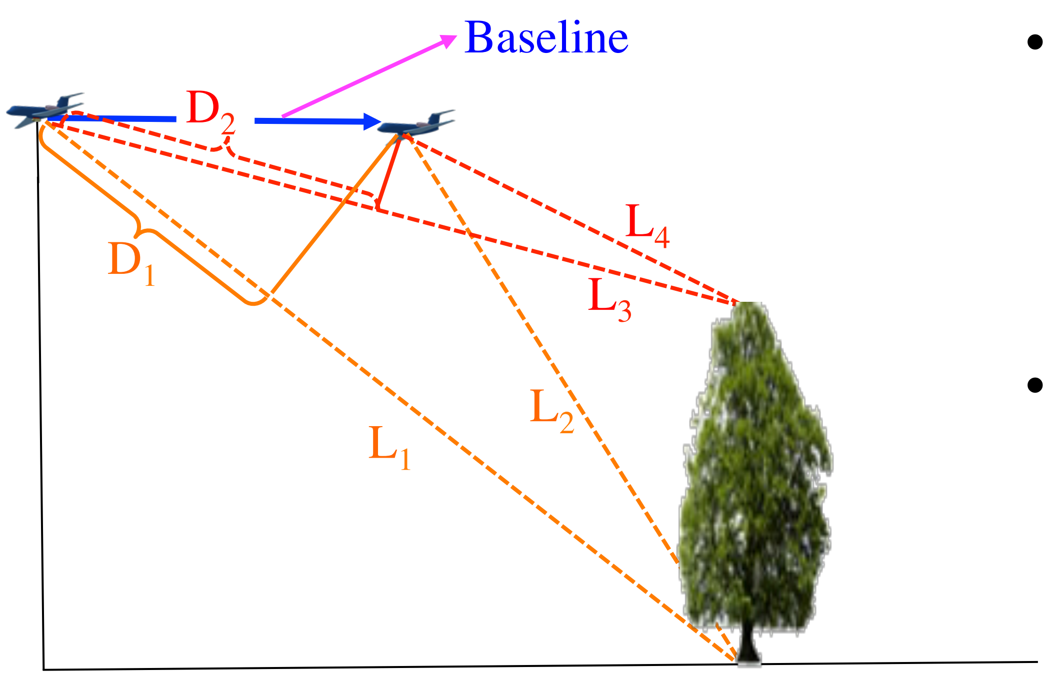
- There can be thousands to billions of wavelengths between a point in the canopy and the radar that combine with random phase obscuring any information about the vertical structure within the volume.



How can the signal be disentangled to obtain vertical information?

Radar Interferometry – Seeing Vertical

- The trick to getting vertical information is to add another observation!
- Interferometry obtains the sub-wavelength **differential** range information from the reflected signals from **two** vantages.
- This information encodes information about the vertical structure.



- So the key observation here is that the **differential** range changes vertically whenever the baseline is not zero.
- Note, this is key difference with lidar, lidar uses one vantage whereas InSAR uses two or more.

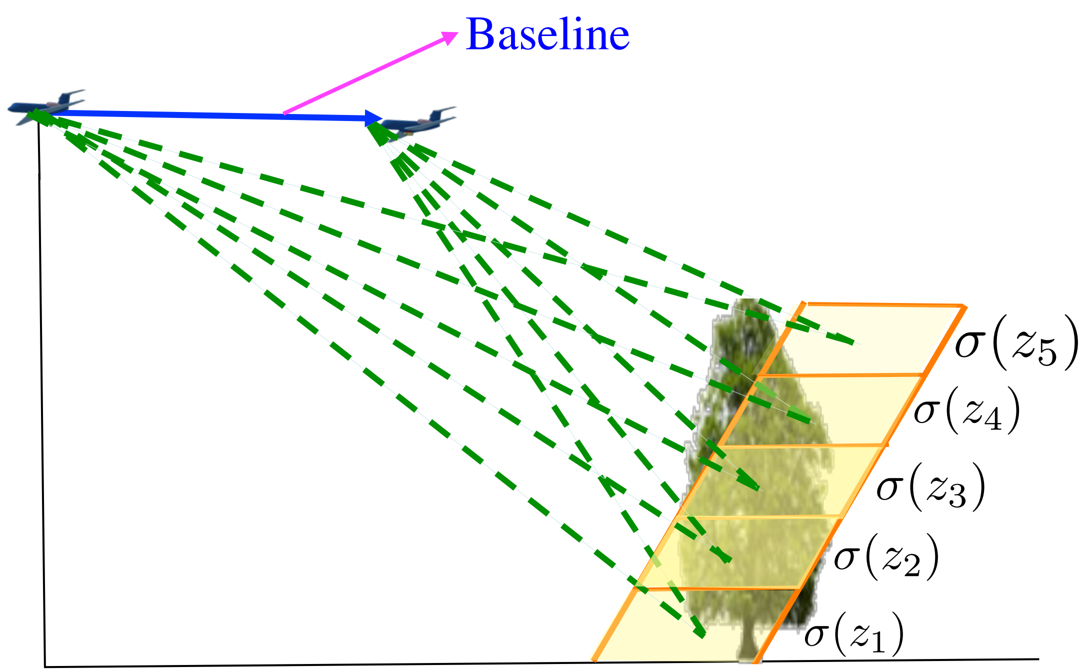
Differential Ranges

$D_1 = L_2 - L_1$ $\quad$ $D_2 = L_4 - L_3$

Differential range can be used to sense the vertical structure

What is InSAR Measuring?

- InSAR measurement has two components:
  - **Scattering component**, σ(z), the depends on the strength of the reflected signal
  - **Geometric component**, F, that depends on the baseline length and measures how fast the differential ranges are changing within a resolution cell



Interferometric Signal

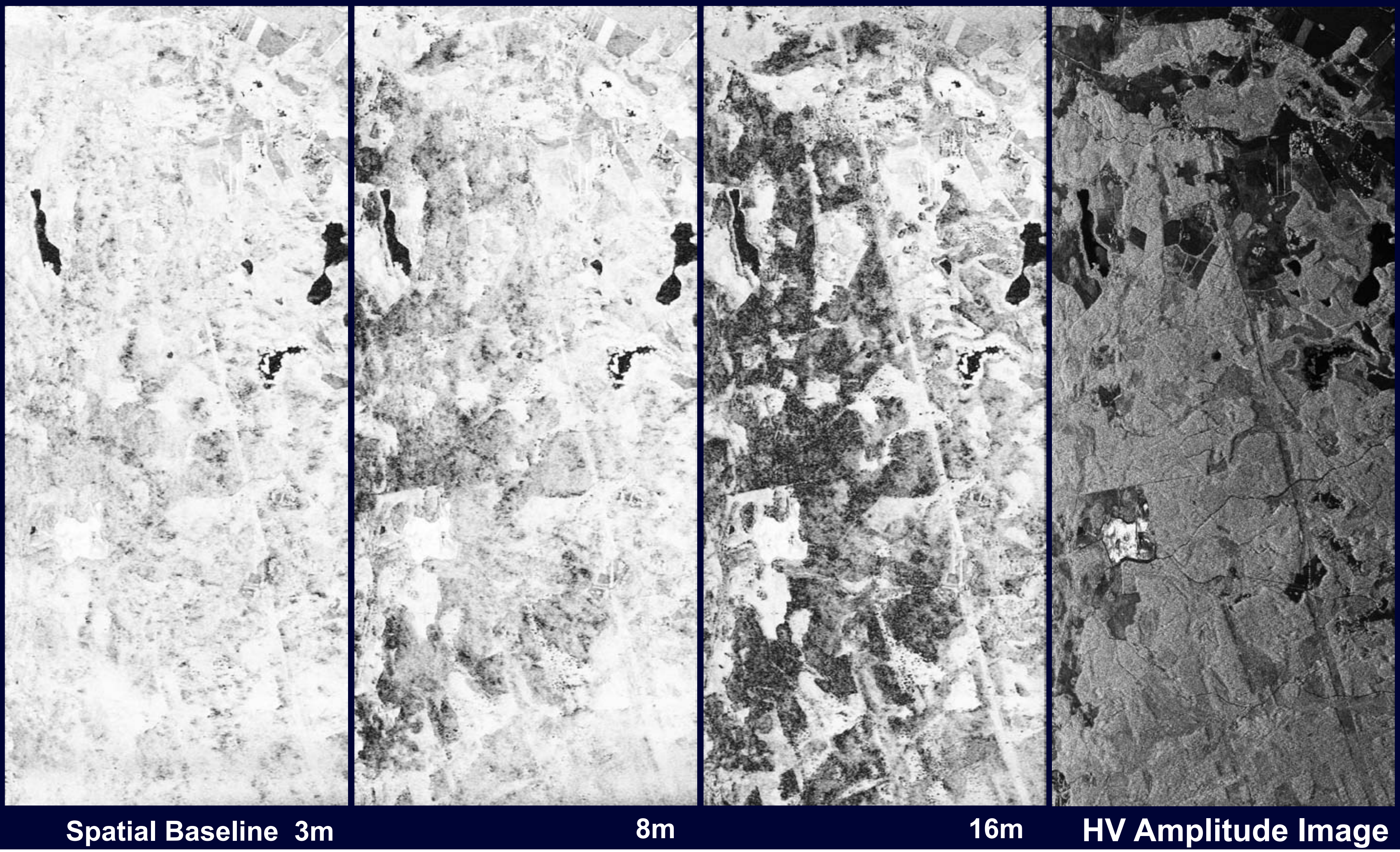
$$\text{InSAR} = \sigma(z_1)F(\vec{b}, z_1) + \sigma(z_2)F(\vec{b}, z_2) + \sigma(z_3)F(\vec{b}, z_3) + \sigma(z_4)F(\vec{b}, z_4) + \sigma(z_5)F(\vec{b}, z_5)$$

Note: $F(0, z) \equiv 1$

- InSAR has sensitivity to volume but with only one observation gives limited visibility to the internal structure within a range cell.

Interferometric Sensitivity to Volume

L-band Volume Sensitivity



Getting Better Resolution Vertically

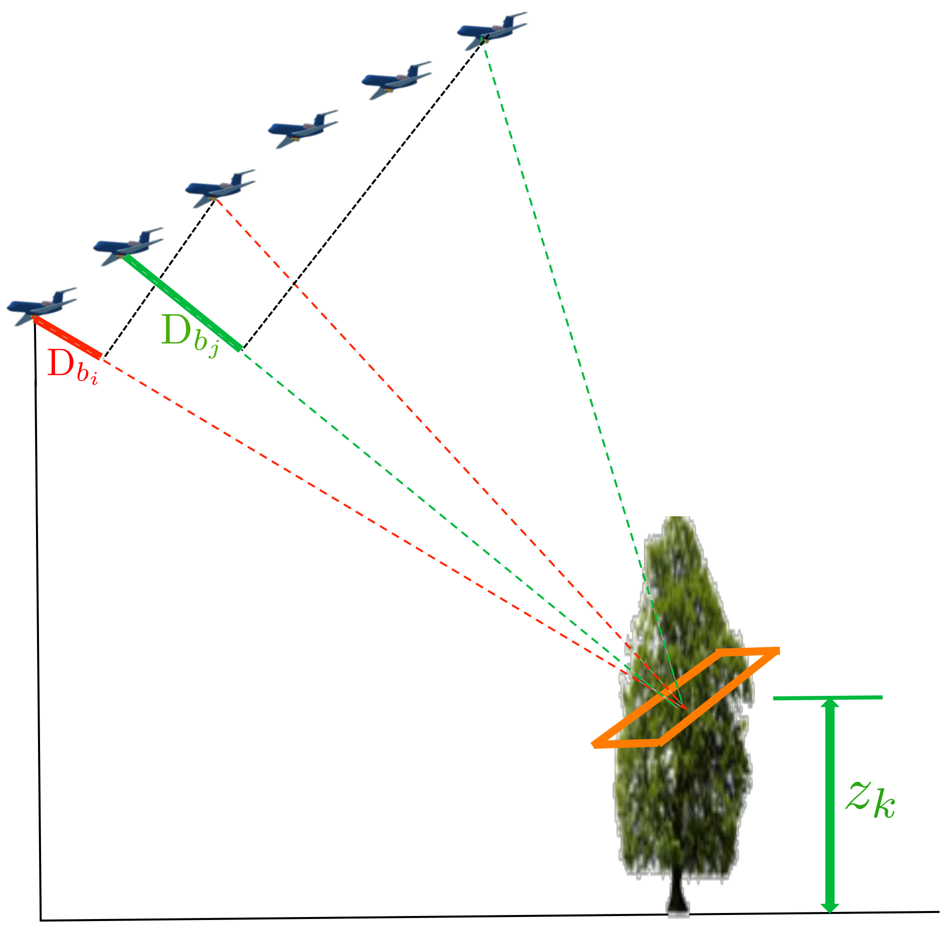
- We just learned that InSAR measurements have two basic components:
  - a scattering component and
  - a geometric component.

- To enhance vertical information we need to have either additional
  - scattering diversity,
  - geometric diversity,
  - or both.

- Find a model that uses a sparse set of available measurements to provide information on vertical structure.
  - Measurements plus model may be sufficient to capture enough detail on vertical structure to support a wide range of ecosystem applications.

Geometric Diversity – Multiple Baselines

- We can use multiple baselines to obtain geometric diversity and thereby achieve finer information vertically.



$$\mathrm{InSAR}_1 = \sum_{k=1}^{5} \sigma(z_k) F(\vec{b}_1, z_k)$$

$$\mathrm{InSAR}_2 = \sum_{k=1}^{5} \sigma(z_k) F(\vec{b}_2, z_k)$$

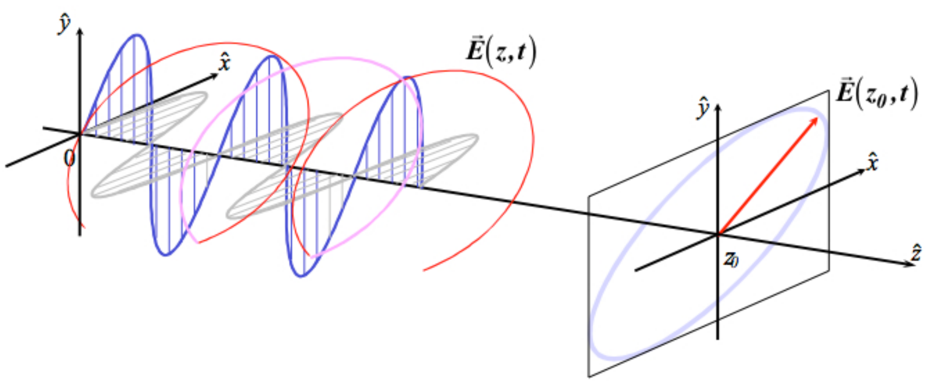
$$\vdots$$

$$\mathrm{InSAR}_N = \sum_{k=1}^{5} \sigma(z_k) F(\vec{b}_N, z_k)$$

Multiple baseline measurements used to solve for vertical profile – or approximation to profile.

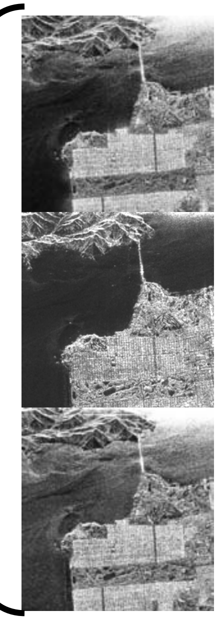
Scattering Diversity - Polarization

- To get backscatter diversity make use of the fact that light is polarized and that different polarizations backscatter different amounts of energy depending on the vegetation structure.



Polarization is determined by direction of electric field.

Image Using Different Polarizations



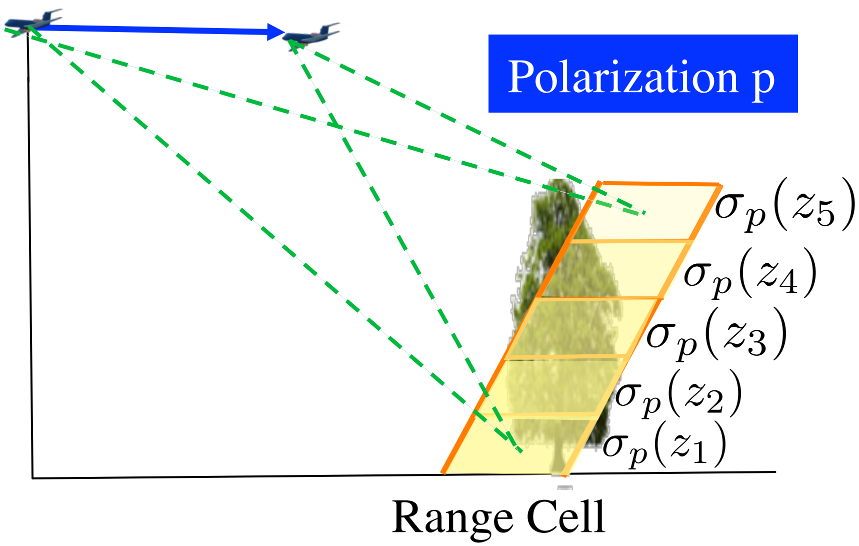
HH

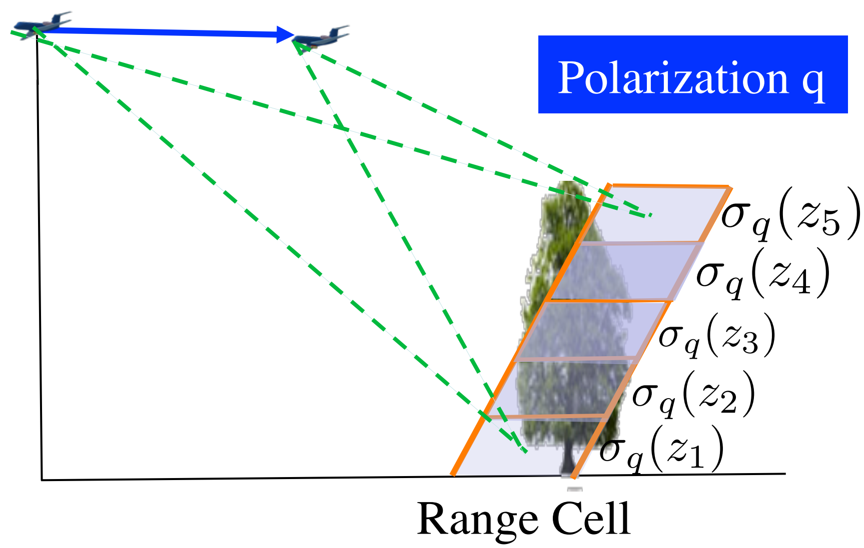
HV

VV

Scattering Diversity - Polarization

- Scattering as function of height within the volume varies with polarization.
  - Parts of the canopy that appear bright(dark) at one polarization may appear dark(bright at another).
- Polarization provides additional information on the structure of the volume.

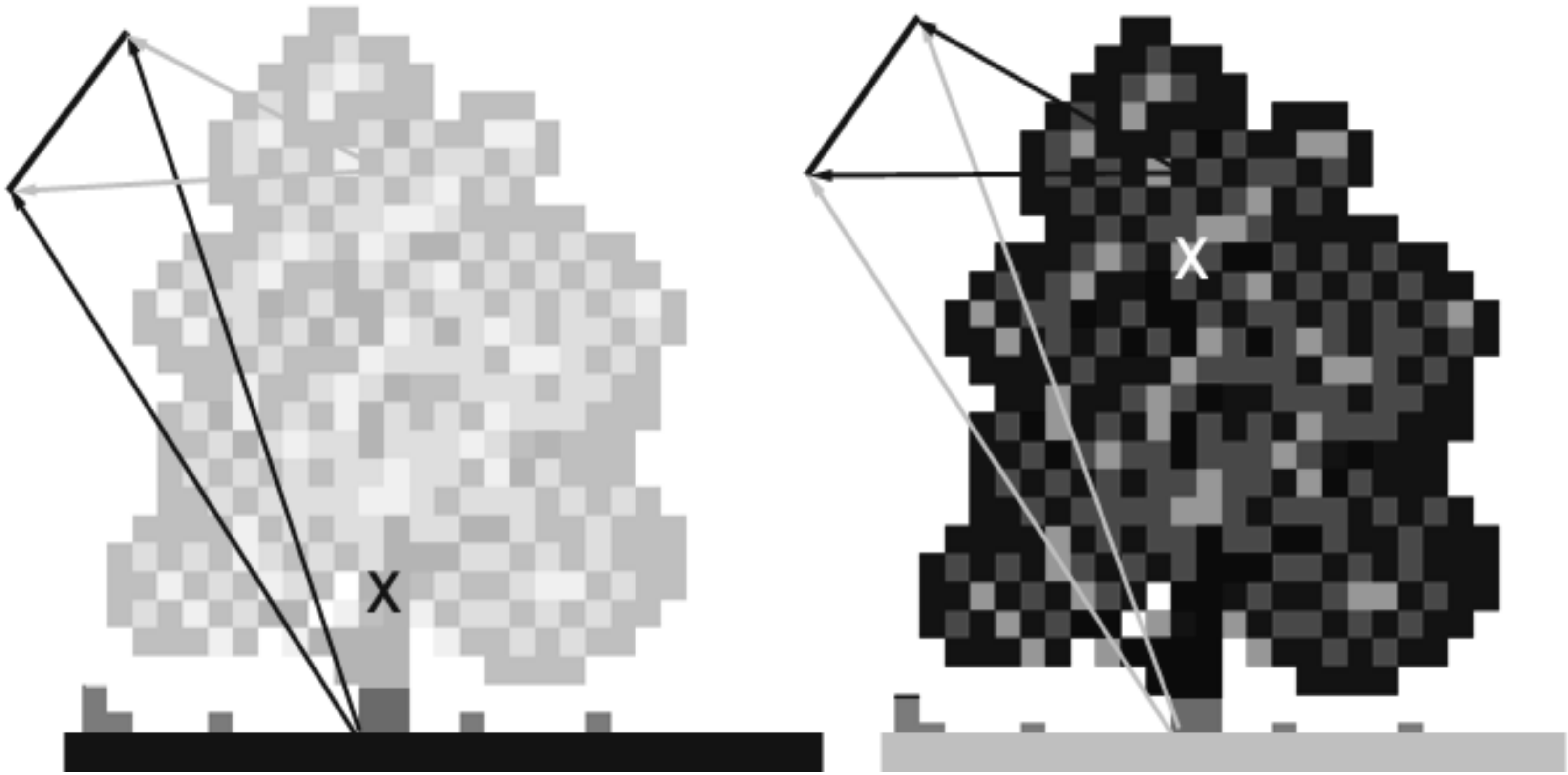




$$\mathrm{InSAR}_p = \sum_{k=1}^{5} \sigma_p(z_k) F(\vec{b}, z_k) \qquad \mathrm{InSAR}_q = \sum_{k=1}^{5} \sigma_q(z_k) F(\vec{b}, z_k)$$

Polarimetric Interferometry

- Effective vertical location in canopy looks different for different polarizations.



PolinSAR Models

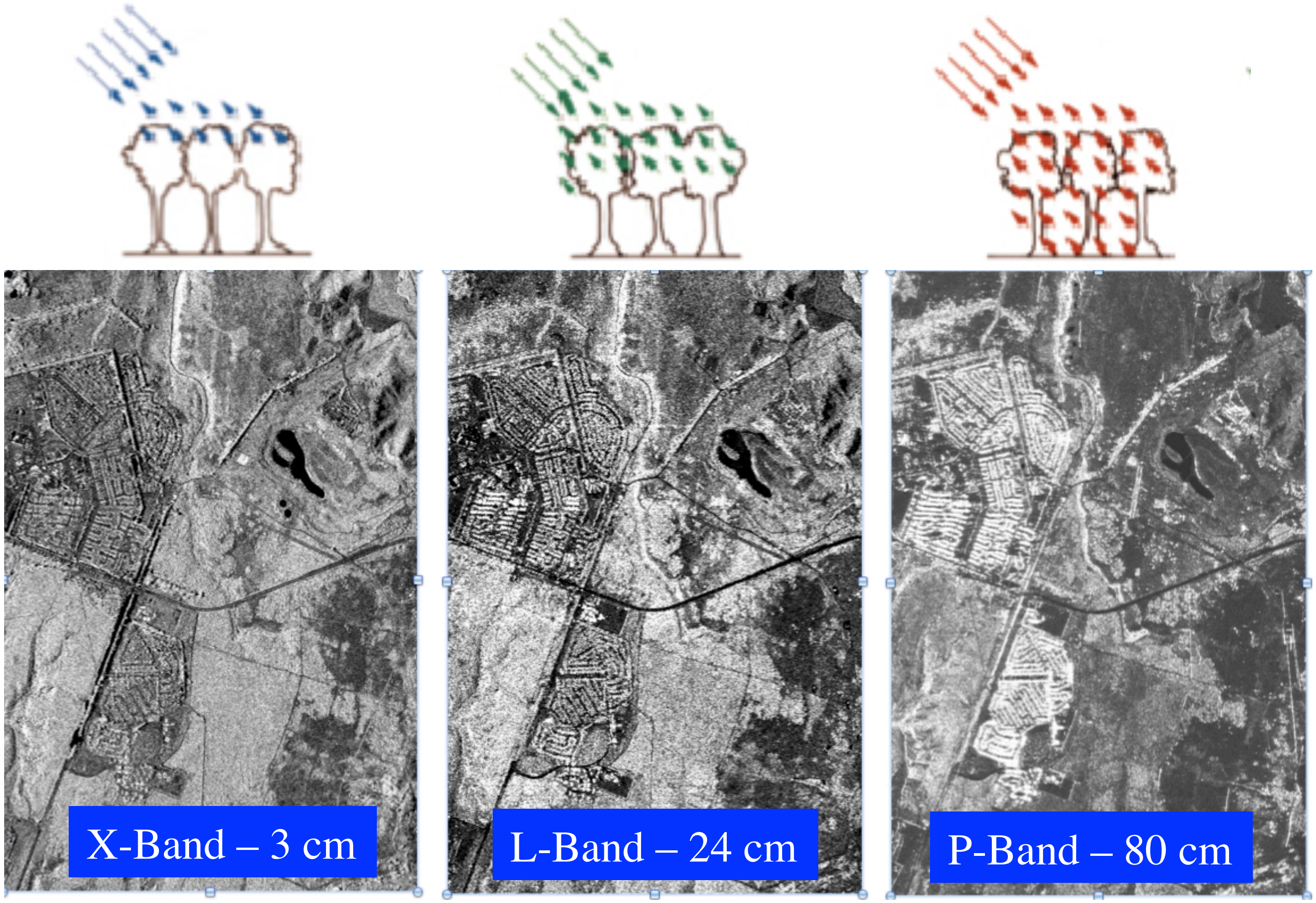
- Adding polarizations may not seem to help at first.
  - If the profiles from different polarizations are not correlated in any way then would have a complete new set of unknowns.

- With modest assumptions about the scattering behavior in vegetation then simple models can be derived linking polarimetric InSAR measurements with structural parameters such as the height.

- The right combination of baseline and polarization diversity is what provides polarimetric interferometry with the ability to sense vertical structure.
  - Vertical structure derived from PolinSAR measurements has been shown in some cases to resemble lidar profiles albeit with reduced vertical resolution.

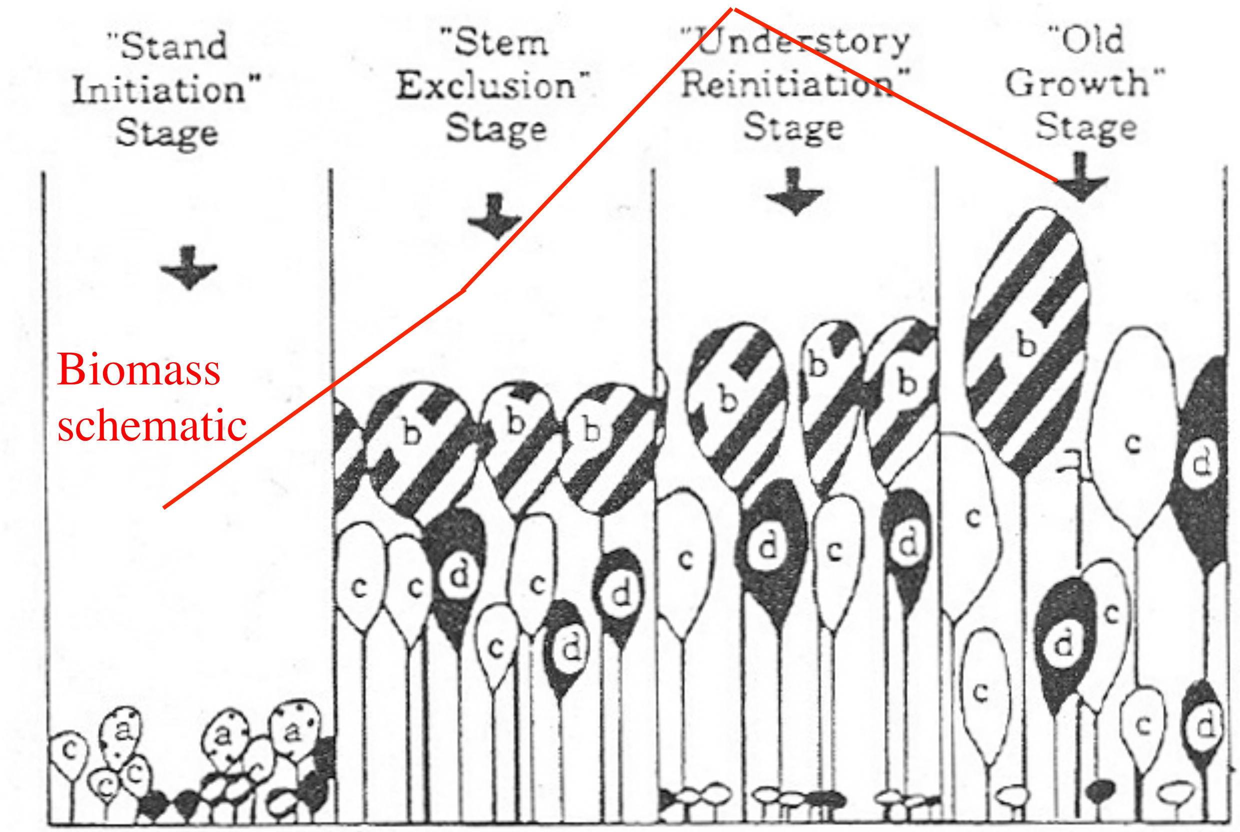
Maximizing Visibility – Use the Right Wavelength

- Different radar wavelengths interact differently with forest canopies.
- Generically, longer wavelengths (lower frequencies) penetrate deeper into the canopy.
  - Backscatter values saturate at higher biomass levels for longer wavelengths.



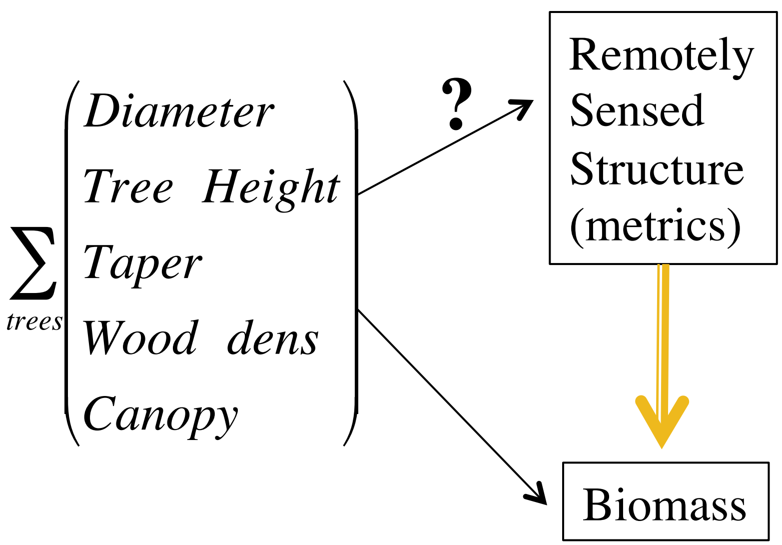
Ecosystem Applications: Biomass

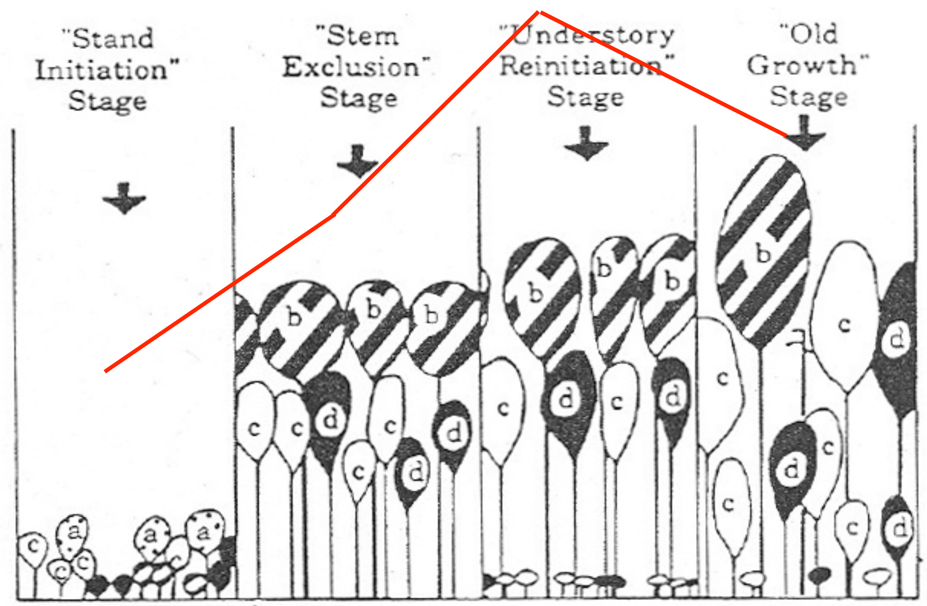
- Field Biomass=Σ_{tree}F(Tree Diameter, tree height, taper, wood density profile, canopy characteristics)
- Remote Sensing Biomass=f(avg height, std dev); =g(CH10%,CH90%, extent); =h(HOME)…



Waring and Running, Forest Ecosystems, 1998; CD Oliver, Forest Ecology and Management, 1981

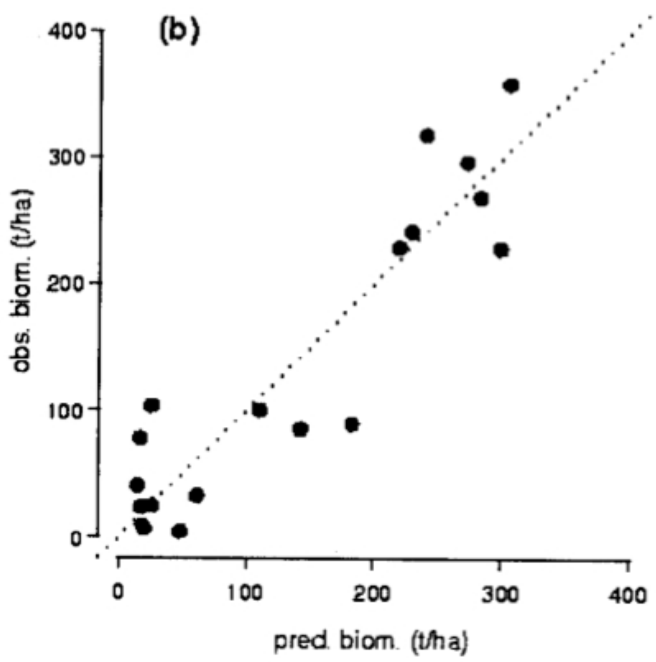
Ecosystem Applications: Biomass

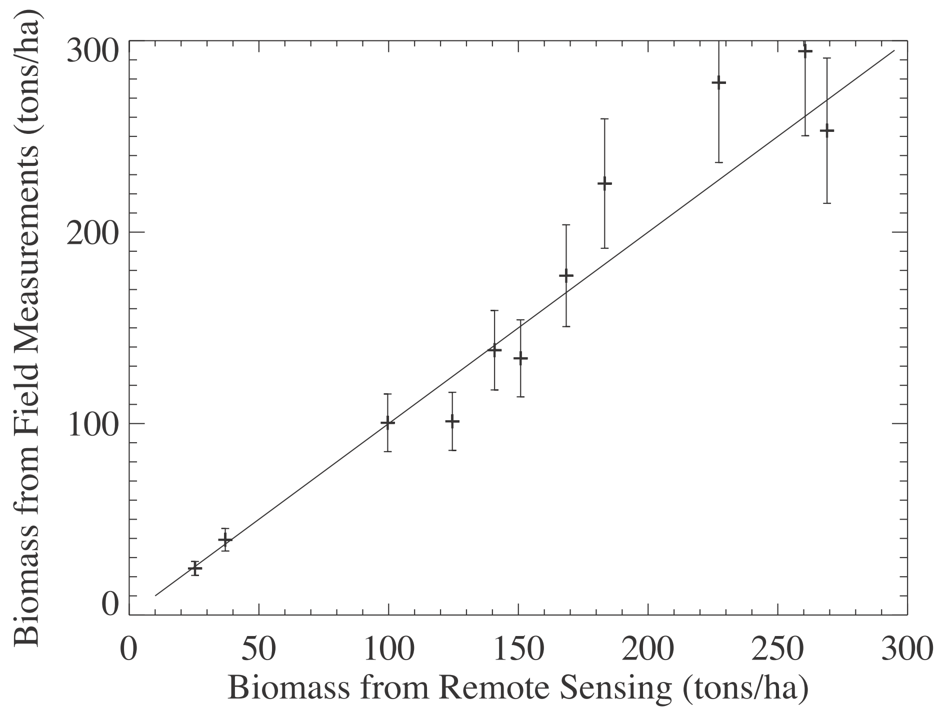




Ecosystem Applications: Biomass

- Various InSAR structural metrics have been used to estimate forest biomass; often in conjunction with other techniques



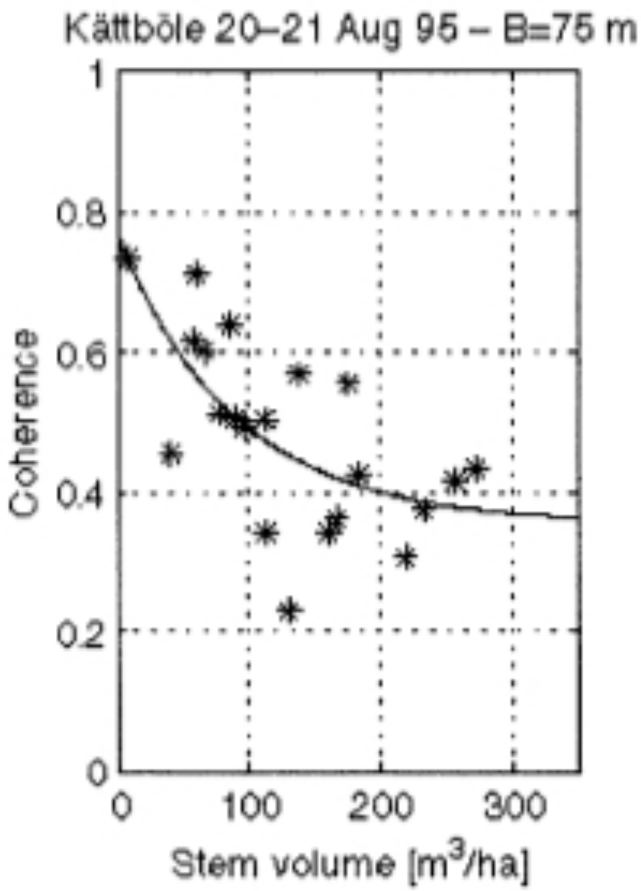


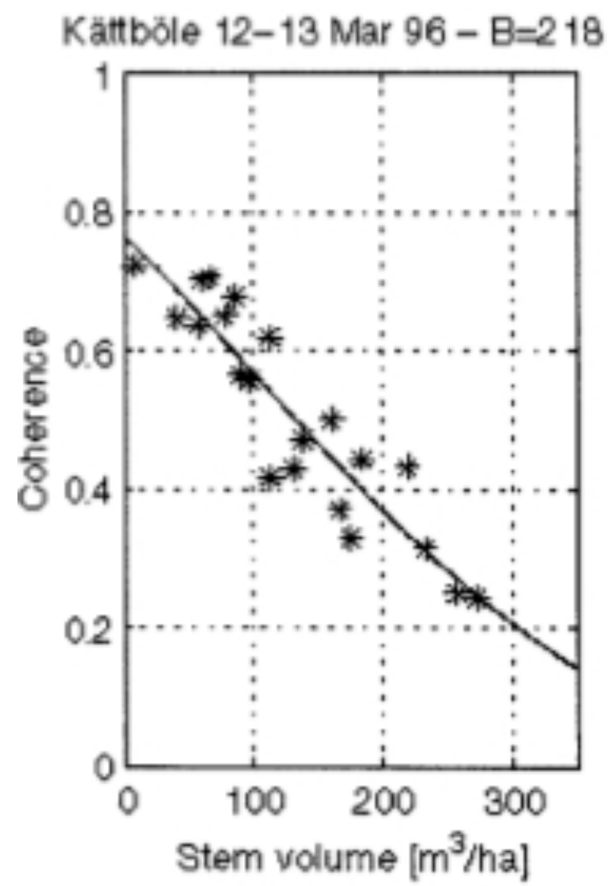
Neef et al. 2005, X-P InSAR height with P-band HH power; biomass range 5-350 Mg/ha, RMS=46 Mg/ha (tropical)

Treuhaft et al. 2003, C-InSAR avg height and standard dev, with hyperspectral LAI; biomass range 30-270 Mg/ha, RMS=25 Mg/ha (temperate)

Ecosystem Applications: Stem Volume

- InSAR coherence, a measure of the broadness of the distribution of the $\sigma(z_i)$'s and temporal decorrelation (dominant below), has been used to establish a correlation with forest stem volume.





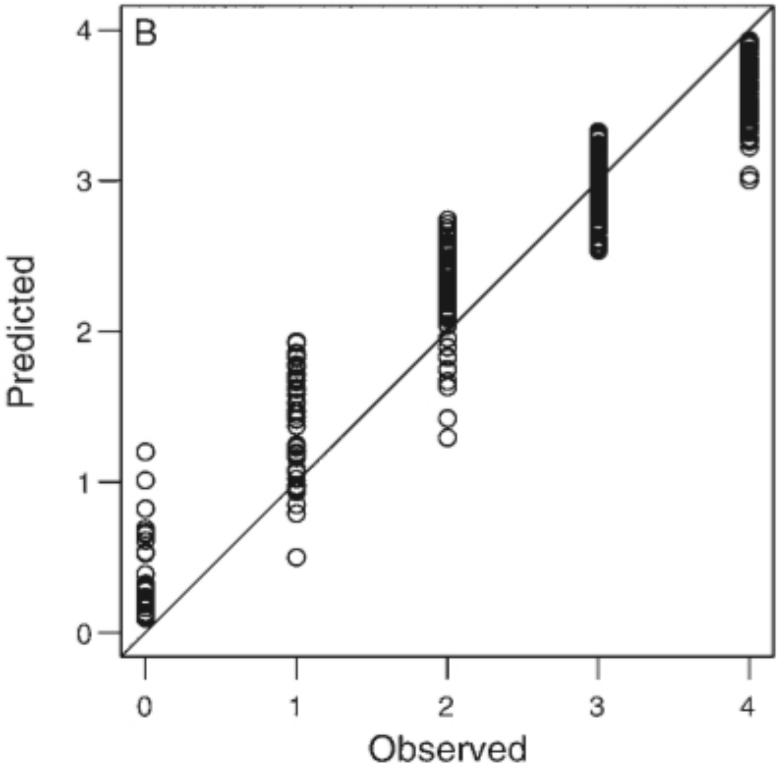
Santoro et al. 2002, C-band InSAR
Coherence versus stem volume, short baseline, rms 88 m^3/ha (boreal)

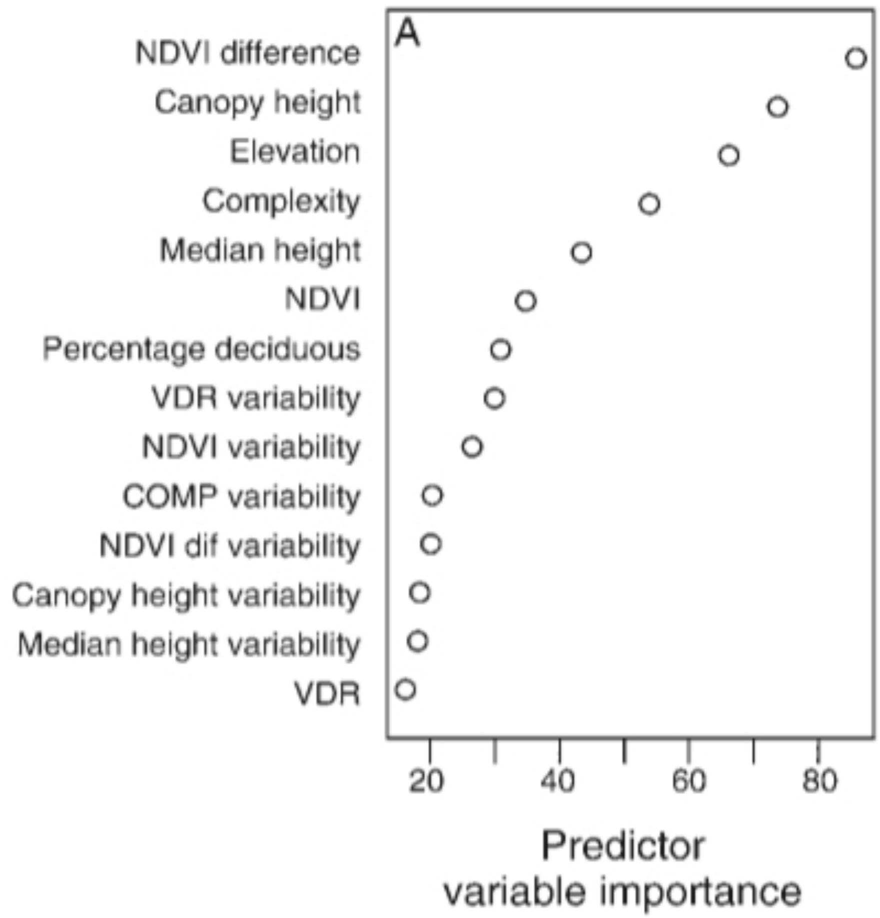
rms 22 m^3/ha, longer baseline

• Temp decor a signal, as in Lavalle et al., in press

Ecosystem Applications: Biodiversity

- Lidar metrics, which can potentially be realized with InSAR, have been used to estimate the presence of black-throated blue warblers





Goetz et al. 2010, Predicted vs observed presence (number of Years in 4 that bird observed)

Importance of remote sensing metrics in presence Estimation. $COMP = -\sum_i p_i \log(p_i)$ Where p_i is the prob of an amplitude of a_i in the waveform

Conclusions

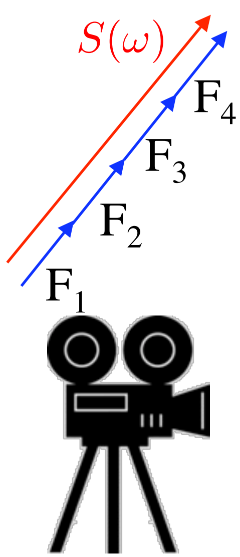
- Why can't radar look nadir and do reflectometry, like lidar?
  - Wavelength of radar makes huge spot on the ground, too big for ecosystems work
- InSAR measurements consist of two components a scattering component and a geometric component that depends on the the baseline length.
  - InSAR **differential** range changes vertically whenever the baseline is not zero
- The right combination of baseline and polarization diversity is what provides polarimetric interferometry with the ability to sense vertical structure.
- Ecosystem applications: What InSAR-derived structure correlates with ecosystem variables?
  - Schematic structure-based biomass estimation
  - Biomass: Average height, standard deviation, total height
  - Stem volume: temporal decorrelation
  - Biodiversity presence (lidar): Canopy height and complexity (vertical nonuniformity

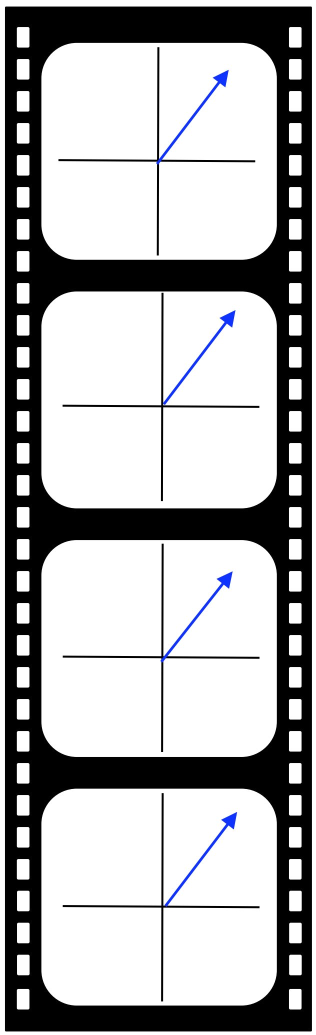
Backup Charts

Fourier Transform

- The Fourier transform is the mathematical tool that takes a signal and determines its frequency content. The basic idea is very simple.

$$\mathcal{F}(s(t))(\omega) = S(\omega) \equiv \int_{-\infty}^{\infty} s(t)e^{-i\omega t}dt$$

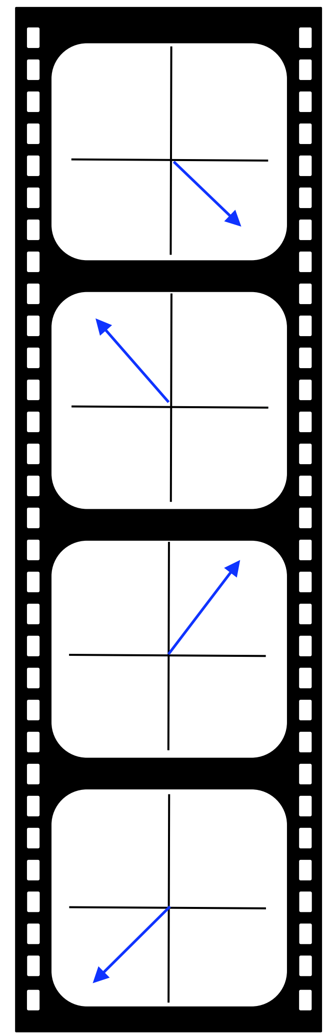


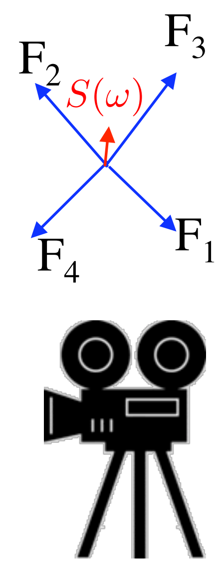


Phasors rotating near the same frequency as the film signal capture the same phasor every time producing a large signal at that frequency.

Phasors rotating at a frequency different from the film are captured at random moments producing a small signal.

For each frequency, ω, of interest we change the scroll speed of the film to one frame every 2π/ω time units.

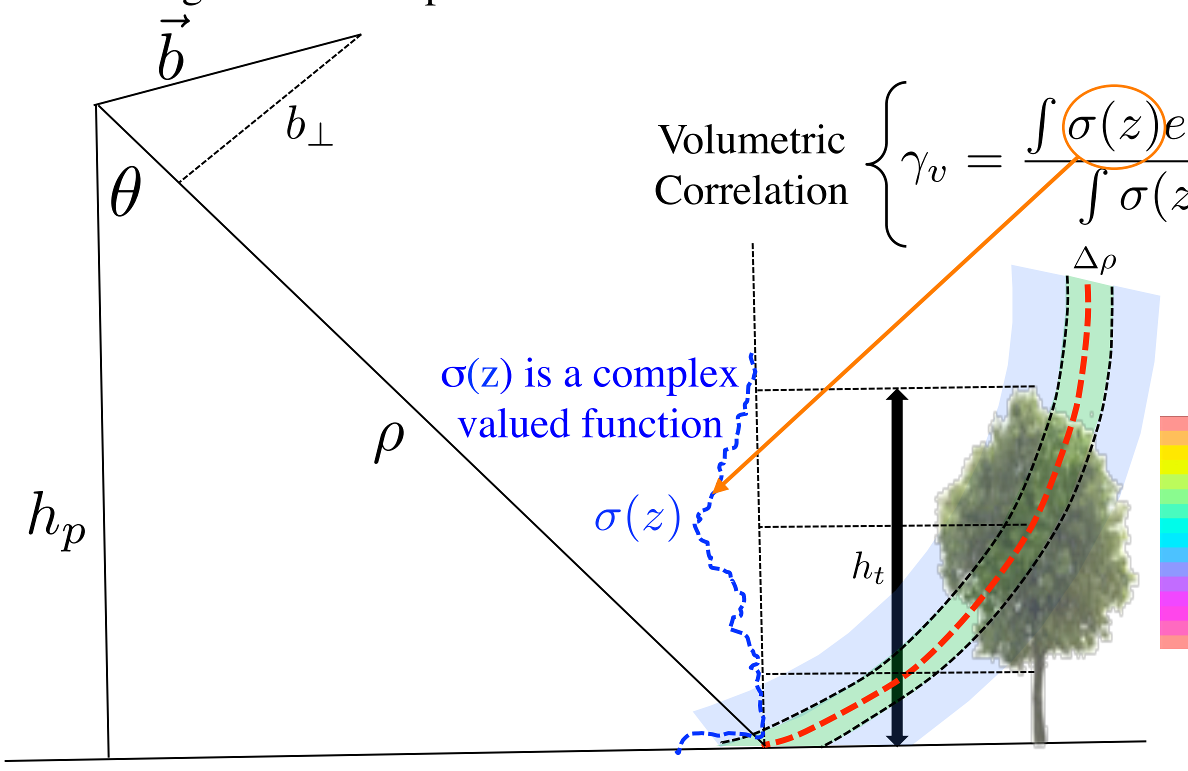




SAR Interferometry and Vertical Structure

- Interferometry uses observations from multiple vantages to obtain information about the vertical structure of the scattering medium.
  - Interferometry is fundamentally a relative measurement between the vantages.
  - $\sigma_{pq}(z)$ is the backscatter, including attenuation, as a function of height within a radar resolution cell. Note that it is polarization and wavelength dependent but is independent of the interferometric baseline.
  - k_z is the vertical wave number and is a measure of how quickly phase is varying vertically within a radar resolution element. It is a function of the imaging geometry, the baseline and the wavelength but is independent of the backscatter function.

Volumetric Correlation $\left\{ \gamma_v = \dfrac{\int \sigma(z) e^{ik_z z} dz}{\int \sigma(z) dz} \right.$ $\qquad 0 \le |\gamma_v| \le 1$



$$k_z = \frac{\partial \phi}{\partial z} = \frac{2\pi p b_\perp}{\lambda \rho \sin\theta} = \frac{2\pi p b_\perp}{\lambda h_p \tan\theta}$$

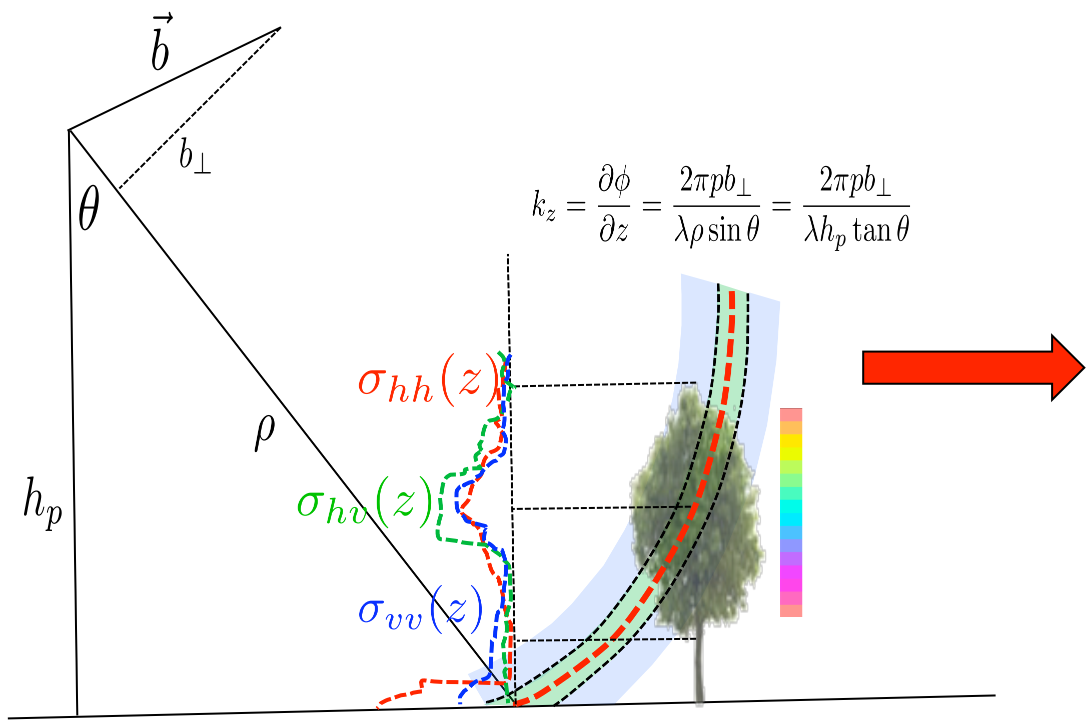
Phase change as a function of height at a FIXED range

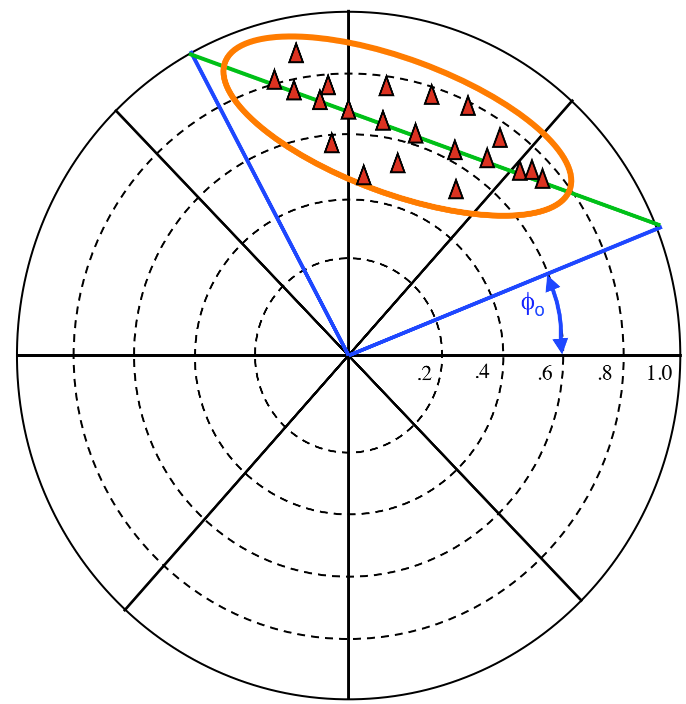
$$h_a = \frac{2\pi}{k_z} \Longrightarrow k_z \approx \kappa \frac{2\pi}{h_t}$$

κ between 0.25 and 1 depending on desired sensitivity

Polarimetric Interferometry

- Since the backscatter function is polarization dependent the volumetric correlation is also polarization dependent. This can be exploited to provide additional information about vertical structure including height.
  - Infinite number of elliptical polarization states can be synthesized from a small polarization basis set (typically HH, HV and VV).
  - Polarization diversity coupled with interferometry improves ability to resolve vertical structure.





Volumetric Correlation
For Different Polarizations